Separately contacted electron-hole double layer in a $GaAs/Al_xGa_{1-x}As$ heterostructure

B. E. Kane, J. P. Eisenstein, W. Wegscheider, L. N. Pfeiffer, and K. W. West
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

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We describe a method for creating closely spaced parallel two-dimensional electron and hole gases confined in 200 Å GaAs wells separated by a 200 Å wide $Al_xGa_{1-x}As$ barrier. Low-temperature ohmic contacts are made to both the electrons and holes, whose densities are individually adjustable between $10^{10}/cm^2$ to greater than $10^{11}/cm^2$. © *1994 American Institute of Physics.*

Parallel layers of a two-dimensional electron gas (2DEG) and a two-dimensional hole gas (2DHG) spaced closely enough together so that electron-hole interactions are important are an extremely interesting system to search for new physics in semiconductor heterostructures. When the layer separation becomes comparable to the spacing between carriers within a layer, new ground states have been predicted in the fractional quantized Hall effect (FQHE) regime.[1] The presence of two carrier types is also expected to radically change the FQHE–Wigner crystal phase boundary.[2] More interestingly, when the layers are sufficiently close, and the densities of the carriers are sufficiently dilute, the electrons and holes will form a 2D Bose gas of stable excitons that is expected to have a superfluid phase transition.[3,4] Finally, if the intervening barrier between the electrons and holes is thin enough that electron-hole annihilation is possible, an electron-hole double layer (EHDL) can be a radiation source in which both the electron-hole combination time and the outgoing photon energy are adjustable parameters.[5,6]

Several technical obstacles have prevented an adequate experimental exploration of the properties of EHDLs.[7] Ideally, a sample should have an electron-hole layer separation comparable to the Bohr radius (typically ~100 Å for semiconductors) with carrier densities such that the mean separation between carriers in the same layer exceeds the layer separation. If the electrons and holes are in equilibrium, these conditions are almost impossible to achieve in most semiconductors without undesirable heavy doping in the vicinity of the EHDL. Equilibrium electron-hole accumulation is possible in $InAs/Al_xGa_{1-x}Sb$ heterostructures,[8,9] because the conduction band of InAs can overlap with the valence band of $Al_xGa_{1-x}Sb$. Unfortunately, the development of this material system is not sufficiently advanced to probe new electron-hole physics. In particular, unintentional doping causes undesirably large, and uncontrollable, electron and hole densities.[10,11]

Perhaps the most promising approach to the problem of making EHDLs is to use the mature materials system of $GaAs/Al_xGa_{1-x}As$ in structures in which the electrons and holes are out of equilibrium. The simplest approach is to illuminate a quantum well in the presence of an electric field that draws photogenerated electron-hole pairs to opposite sides of the well. Optical generation of the EHDL, however, suffers from the drawback that the EHDL is short-lived and can only be probed using optical techniques that have tended to give ambiguous results.[12,13]

A preferable alternative is to make separate electrical contacts to the electron and hole layers, using external biases to create a nonequilibrium steady-state population of electrons and holes. While this method introduces an unavoidable increase in the complexity of the structures to be measured, they may be probed with the standard techniques that have been most effective for studying the FQHE and Wigner crystal regime in single layer systems. This path was taken by Sivan, Solomon, and Shtrikman,[14] who fabricated a structure containing a 200 Å thick $Al_xGa_{1-x}As$ barrier separating wide GaAs layers. By making n contact to the top GaAs layer and p contact to the bottom GaAs layer, and by appropriately biasing the contacts, they were able to induce electron and hole gases on the top and bottom sides of the $Al_xGa_{1-x}As$ barrier. Their electrical contacts, however, failed at low temperatures ($T<10$ K) and low densities ($<5\times10^{10}/cm^2$), precisely the regime where new physics is most likely to occur.[15]

We have developed a technique for creating closely spaced 2DEGs and 2DHGs confined in 200 Å wide GaAs wells separated by a 200 Å ($Al_xGa_{1-x}As(x=0.3)$) barrier. Electrical contact to the electrons and holes is maintained at the lowest temperatures we have used ($T=0.3$ K), and the densities of both types of carriers are adjustable from $\sim10^{10}/cm^2$ to $>10^{11}/cm^2$. Our approach is shown schematically in Fig. 1(a). The bottom well is modulation doped with electrons, which are contacted using standard NiGeAu n-type alloyed contacts. The doping does not extend across the entire sample, however, since part of it is covered during Si deposition with an *in situ* shadow mask.[16] The hole gas is induced by applying a sufficiently large negative voltage to an n^+ GaAs top gate, one of whose edges is self-aligned to an AuBe p-type contact using a process identical to the one we have described previously for making gated 2DEGs or 2DHGs.[17]

Because the modulation doping does not extend to the p-type contact and the gate does not extend to the n-type contact, electrons and holes both can accumulate in adjacent wells only where the gate overlaps the doped region. The valence and conduction band edges in the overlap region, under biases appropriate for simultaneous electron and hole accumulation, are shown in Fig. 1(b). The gate bias V_G and the electron-hole potential difference V_{eh} are set externally. (We define $VG_{electrons}=0$.) Control of these voltages allows for separate adjustability of both the electron density n and the hole density p. Note that the absence of an electric field

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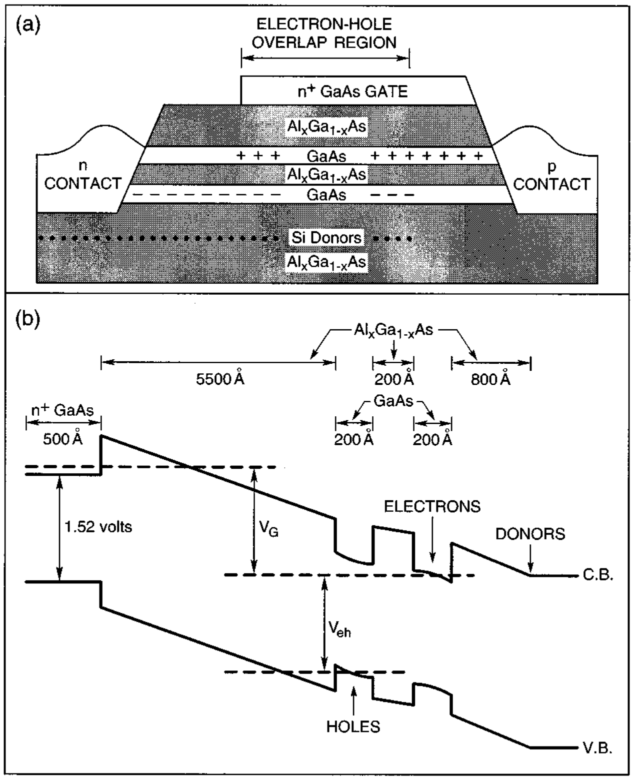

FIG. 1. (a) Schematic representation of our device. (b) Valence and conduction band edges in the electron-hole overlap region when the device is biased for simultaneous electron and hole accumulation.

(the flatband condition) in the barrier between the wells implies that $V_{eh}=1.52$ V, the GaAs band gap.

A photograph of one of our devices is shown in Fig. 2. Two separate self-aligned p-type contacts are made to facilitate measurements of the contact resistance to the holes (typically 1–10 kΩ when holes are present). The gated region extends out from the p-contacts and overlaps with the electron doped region in a 50 μm $\times$200 μm rectangle. The region surrounding the gate is defined by etching away the 500 Å top n^+ layer. Since the Fermi level is pinned near midgap at the etched surface, this surface will become negatively charged in regions where the sample is doped. This negative charge attracts holes and can cause an undesired 2DHG to occur in the top well outside the gated region. If this 2DHG extends to the n contacts, a leakage current will appear. Consequently, the n^+ top is only etched away in a narrow region surrounding the gate. The exterior n^+ region is always held at the potential of the underlying 2DEG.

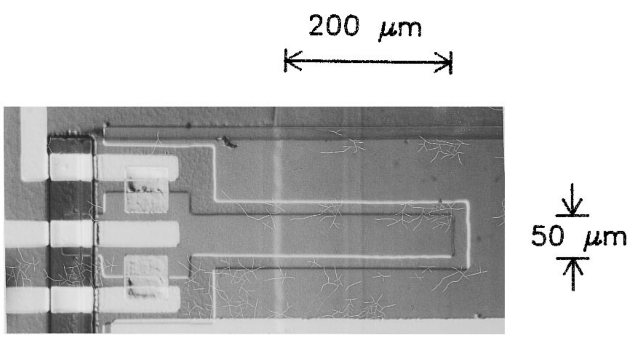

FIG. 2. Photograph of our device. The gold squares are the self-aligned p-type contacts. The gate extends horizontally across to overlap the electron modulation doped region, which is to the right of the diffuse vertical line near the center. The 2DEG and 2DHG overlap in the rectangular region indicated. The n-type contacts are outside the region shown.

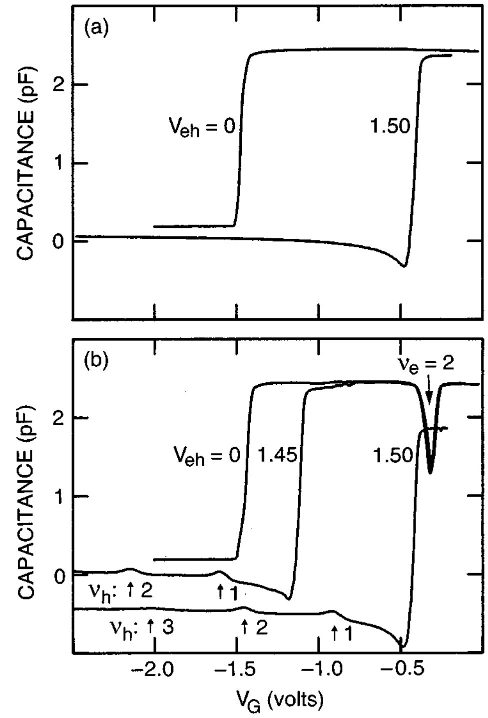

FIG. 3. (a) Capacitance between the top gate and the electrons when only electrons are present ($V_{eh}=0$) and when holes accumulate prior to electron depletion ($V_{eh}=1.50$ V). Onset of hole accumulation is indicated by a sharp drop in the capacitance signal to a negative value. (b) Similar data taken when $B=3.0$ T. The trace taken when $V_{eh}=1.50$ is offset for clarity.

To demonstrate that simultaneous electron and hole accumulation is occurring in our samples, we have used a powerful capacitance technique developed by Eisenstein,[18] applicable to separately contacted double layer systems. With V_{eh} held constant, a 10 mV ac modulation ($\nu=1592$ Hz) is applied to the top gate in addition to the dc V_G. The ac current flowing from the *bottom* (electron) layer is then measured using a current sensitive preamplifier. When no holes are in the top well, the signal is just the capacitance C between the gate and the 2DEG in the region where they overlap. When a 2DHG is present between the 2DEG and the top gate, most of the capacitance between the gate and the 2DEG is eliminated, as would be expected from classical electrostatics. A small "leakage" signal is predicted by quantum mechanics that is proportional to $d\mu_h/dp$, the derivative of the chemical potential of the intervening 2DHG with respect to its density.[18]

Data are shown in Fig. 3(a) for our device when $T=1.5$ K. When $V_{eh}=0$, simultaneous electron-hole accumulation is impossible. C is constant until V_G is sufficiently negative to deplete all electrons under the gate, when C falls to nearly zero. (The density of the 2DEG in the bottom well when

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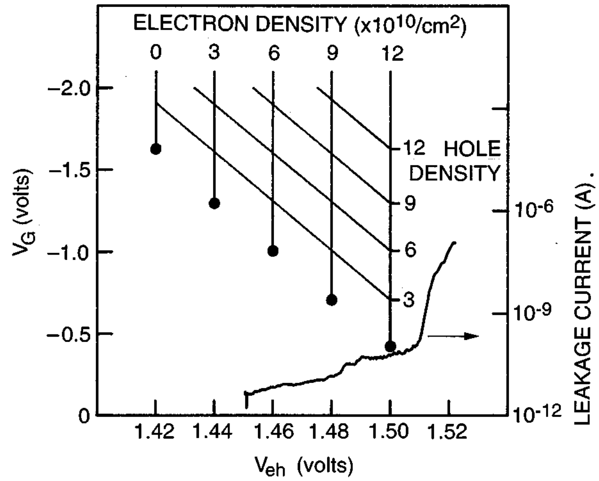

FIG. 4. Black dots are the experimentally measured thresholds for accumulation of holes at different values of V_{eh}. Beyond threshold, the approximate electron and hole densities are shown schematically. Typical leakage current (measured coming out of the electron contact) is shown for $V_G = -1.0$ V.

$V_G=0$ is $1.6 \times 10^{11}/\mathrm{cm}^2$. The -1.5 V value of V_G required for depletion of the 2DEG is only fortuitously equal to the GaAs band gap.) When $V_{eh}=1.50$ V, hole accumulation occurs in the top well prior to depletion of electrons in the bottom well, and it causes a sudden drop in C to a *negative* value. This negative divergent behavior of C for small p is also seen in electron double layers[18] and is attributable to the dominance of the exchange energy contribution to $\mu_h(\mu_h \propto -p^{1/2}$, $d\mu_h/dp \propto -1/p^{1/2})$ at low densities.

Additional evidence of simultaneous electron-hole accumulation is seen when a magnetic field (B) is applied perpendicular to the electron and hole layers [Fig. 3(b)]. Because of the large difference between spin splitting and orbital Landau level splitting for electrons in GaAs, structure is seen primarily at $\nu_e=2$ in the capacitance when $V_{eh}=0$. In contrast, when holes are present, the structure appearing at $\nu_h=1$ and $\nu_h=2$ is similar, reflecting the much larger effective mass of the holes.

As is seen in Fig. 3(b), the threshold for hole accumulation shifts as V_{eh} is varied. The position of this threshold is plotted as a function of V_{eh} in Fig. 4. The threshold extrapolates to zero when V_{eh} approximately equals the GaAs band gap. For $V_{eh} < 1.42$ V, the electrons are depleted by V_G prior to accumulation of holes. The approximate density of electrons and holes for different values of V_{eh} and V_G is also plotted. Leakage between the electron and hole layers or between the gate and the carriers impedes measurements when $V_{eh} > 1.50$ V or when $V_G < -2.5$ V. At the low electron and hole densities ($< 5 \times 10^{10}/\mathrm{cm}^2$) where the EHDL is potentially most interesting, leakage is of order 1 pA or less.

While a small current leakage has negligible impact on measurements, energetic carriers (generated either by Auger processes or by electrons tunneling from the top gate) can reach the dopant layer and neutralize or ionize donors. This manifests itself in our samples by slow variations in the 2DEG density at low T that impede careful measurements of the EHDL. For this reason, devices using top and bottom gates are probably preferable (although more complicated) to our bottom doped design.

We should emphasize that in our structures, the carrier densities near the contacts are always larger than the densities within the overlap region, and measurements can consequently be made at low ($\sim 10^{10}/\mathrm{cm}^2$) densities without contact failure. Also, our method for making separate contact to the electron and hole layers does not rely on precise depth positioning of the contacts, and should not become more difficult as the intervening barrier thickness is reduced. Finally, we have employed the capacitance probing technique because of its simplicity. In future samples, conventional transport measurements of the electrons and holes in the overlap region should be possible.

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